

A theoretical study on spin coating technique

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Abstract. A comprehensive theory of the spin coating technique has been reviewed and the basic principles and parameters controlling the process are clearly highlighted, which include spin speed, spin time, acceleration and fume exhaust. The process generally involves four stages: a dispense stage, substrate acceleration stage, a stage of substrate spinning at a constant rate and fluid viscous forces dominate fluid thinning behaviour and a stage of substrate spinning at a constant rate and solvent evaporation dominates the coating thinning behaviour. The study also considered some common thin film defects associated with this technique, which include comet, striation, chunks marks environmental sensitivity and edge effect and possible remedies.

Keywords: substrate; centrifugal force; spin coating; thin film; photolithography; acceleration

1. Introduction

Spin coating is a procedure used to apply uniform thin films to flat substrates. A typical process involves depositing a small puddle of a fluid resin onto the center of a substrate and then spinning the substrate at high speed (typically around 3000 rpm) (Mitzi *et al.* 2004). Centrifugal force will cause the resin to spread to, and eventually off, the edge of the substrate leaving a thin film of resin on the surface. Final film thickness and other properties will depend on the nature of the resin (viscosity, drying rate, percent solids, surface tension, etc.) and the parameters chosen for the spin process. Factors such as final rotational speed, acceleration, and fume exhaust contribute to how the properties of coated films are defined (Hellstrom 2007, Mitzi *et al.* 2004). A machine used for spin coating is called a spin coater, or simply spinner.

Rotation is continued while the fluid spins off the edges of the substrate, until the desired thickness of the film is achieved. The applied solvent is usually volatile, and simultaneously evaporates. So, the higher the angular speed of spinning, the thinner the film. The thickness of the film also depends on the concentration of the solution and the solvent (Hellstrom 2007).

Spin coating is widely used in micro-fabrication, where it can be used to create thin films with thicknesses below 10 nm. It is used intensively in photolithography, to deposit layers of photoresist about 1 micrometre thick (Hanaor *et al.* 2011). Photoresist is typically spun at 20 to 80 revolutions per second for 30 to 60 seconds. Owing to the low values of thickness which can be achieved using spin coating methods, this method is often employed in the fabrication of transparent

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titanium dioxide thin films on quartz or glass substrates, such thin film coatings may exhibit self-cleaning and self-sterilizing properties (Hanaor *et al.* 2011).

One of the most important factors in spin coating is repeatability. Subtle variations in the parameters that define the spin process can result in drastic variations in the coated film (Middleman and Hochberg 1993). In spite of few studies regarding to the spin coating method, it has substantial merits, such as the easy control and handling of chemicals and substrates, and fabrication of thin film at faster rates (Ilican *et al.* 2008, Mihi *et al.* 2006). This study has considered a comprehensive description of spin coating process and theory, aimed at equipping intending users of this thin film deposition technique with adequate knowledge to enhance better results.

2. Description of spin coating process

There are four distinct stages to the spin coating process. These include:

2.1 A dispense stage

A typical spin process consists of a dispense step in which the resin fluid is deposited onto the substrate surface as in Fig. 1(a). Two common methods of dispense are Static dispense, and Dynamic dispense. Static dispense is simply depositing a small puddle of fluid on or near the center of the substrate. This can range from 1 to 10 cc depending on the viscosity of the fluid and the size of the substrate to be coated (Hellstrom 2007, Middleman and Hochberg 1993). Higher viscosity and or larger substrates typically require a larger puddle to ensure full coverage of the substrate during the high speed spin step. Dynamic dispense is the process of dispensing while the substrate is turning at low speed. A speed of about 500 rpm is commonly used during this step of the process (Hellstrom 2007, Middleman and Hochberg 1993). This serves to spread the fluid over the substrate and can result in less waste of resin material since it is usually not necessary to deposit as much to wet the entire surface of the substrate. This is a particularly advantageous method when the fluid or substrate itself has poor wetting abilities and can eliminate voids that may otherwise form (Schubert and Dunkel 2003, http://www.holmarc.com/spin_coating_machine.html. Retrieve on February 18 2013).

2.2 Substrate acceleration stage

This stage is usually characterized by aggressive fluid expulsion from the wafer surface by the rotational motion (Meyerhofer 1978, Miitzi *et al.* 2004). Because of the initial depth of fluid on the wafer surface (Fig. 1(b)), spiral vortices may briefly be present during this stage; these would form as a result of the twisting motion caused by the inertia that the top of the fluid layer exerts while the wafer below rotates faster and faster. Eventually, the fluid is thin enough to be completely co-rotating with the wafer and any evidence of fluid thickness differences is gone. Ultimately, the wafer reaches its desired speed and the fluid is thin enough that the viscous shear drag exactly balances the rotational accelerations (Meyerhofer 1978, Miitzi *et al.* 2004).

Typical spin speeds for this stage range from 1500-6000 rpm, again depending on the properties of the fluid as well as the substrate. This step can take from 10 seconds to several

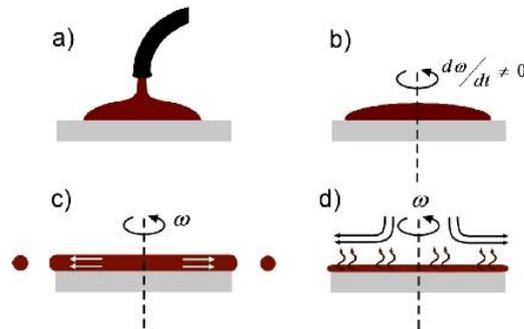


Fig. 1 Four distinct stages to spin coating (Hellstrom 2007)

minutes. The combination of spin speed and time selected for this stage will generally define the final film thickness (Meyerhofer 1978, Miitzi *et al.* 2004). In general, higher spin speeds and longer spin times create thinner films. The spin coating process involves a large number of variables that tend to cancel and average out during the spin process and it is best to allow sufficient time for this to occur (Meyerhofer 1978, Miitzi *et al.* 2004).

2.3 A stage of substrate spinning at a constant rate and fluid viscous forces dominate fluid thinning behaviour

This stage is characterized by gradual fluid thinning. Fluid thinning is generally quite uniform (as in Fig. 1(c)), though with solutions containing volatile solvents, it is often possible to see interference colours “spinning off”, and doing so progressively more slowly as the coating thickness is reduced (Hanaor *et al.* 2011). Edge effects are often seen because the fluid flows uniformly outward, but must form droplets at the edge to be flung off. Thus, depending on the surface tension, viscosity, rotation rate, etc., there may be a small bead of coating thickness difference around the rim of the final wafer (Hanaor *et al.* 2011, Meyerhofer 1978). Mathematical treatments of the flow behaviour show that if the liquid exhibits Newtonian viscosity (i.e., is linear) and if the fluid thickness is initially uniform across the wafer (albeit rather thick), then the fluid thickness profile at any following time will also be uniform leading to a uniform final coating (under ideal circumstances) (Middleman and Hochberg 1993 and Emslie *et al.* 1958).

2.4 A stage of substrate spinning at a constant rate and solvent evaporation dominates the coating thinning behavior

As the prior stage advances, the fluid thickness reaches a point where the viscosity effects yield only rather minor net fluid flow. At this point, the evaporation of any volatile solvent species will become the dominant process (Fig. 1(d)) occurring in the coating. In fact, at this point the coating effectively “gels” because as these solvents are removed the viscosity of the remaining solution will likely rise effectively freezing the coating in place (Peeters and Remoortere 2008, Meyerhofer 1978). (This behaviour was used in the seminal work of Meyerhofer where he quantified the coating thickness dependence on spin speed and viscosity and its relationship to the evaporation rate.) (Meyerhofer 1978)

After spinning is stopped many applications require that heat treatment or “firing” of the coating be performed (as for “spin-on-glass” or sol-gel coatings). On the other hand, photoresists usually undergo other processes, depending on the desired application/use.

Clearly stages (iii) and (iv) describe two processes that must be occurring simultaneously throughout all times (viscous flow and evaporation). However, at an engineering level the viscous flow effects dominate early on while the evaporation processes dominate later (Meyerhofer 1978, Schubert and Dunkel 2003).

3. Theory of spin coating

3.1 Mathematical modelling of spin coating

Spin speed is one of the most important factors in spin coating. The speed of the substrate (rpm) affects the degree of radial (centrifugal) force applied to the liquid resin as well as the velocity and characteristic turbulence of the air immediately above it (Hellstrom 2007). In particular, the high-speed spin step generally defines the final film thickness (see Fig. 2). Relatively minor variations of ± 50 rpm at this stage can cause a resulting thickness change of 10% (Hellstrom 2007). Film thickness is largely a balance between the force applied to shear the fluid resin towards the edge of the substrate and the drying rate which affects the viscosity of the resin. As the resin dries, the viscosity increases until the radial force of the spin process can no longer appreciably move the resin over the surface. At this point, the film thickness will not decrease significantly with increased spin time (Peeters and Remoortere 2008, Emslie *et al.* 1958).

Using cylindrical polar co-ordinates (r, θ, z) with origin at the center of rotation, z perpendicular to the plane, and the axes r and θ of rotating with the plane with angular velocity ω , the balance between viscous and centrifugal forces per unit volume for Newtonian fluid is given by (Emslie *et al.* 1958, Panigrahi *et al.* 2008 and Nirajan *et al.* 2009)

$$-\eta \frac{\partial^2 v}{\partial z^2} = \rho \omega^2 r \quad (1)$$

where η is the absolute viscosity, ρ is the fluid density and v is the fluid velocity in the radial direction of r . Integrating twice with respect to z and using suitable boundary condition that at the free surface of the fluid the shear is zero; that is $\partial v / \partial z = 0$ at $z = h$ we have (Panigrahi *et al.* 2008, Nirajan *et al.* 2009, deBruijne Lammers 1999, Peeters and Remoortere 2008)

$$V = \frac{1}{\eta} \left(-\frac{1}{2} \rho \omega^2 r z^2 + \rho \omega^2 r h z^2 \right) \quad (2)$$

The radial flow q , per unit length of the circumference is given by

$$q = \int_0^h v(z) dz = \frac{\rho \omega^2 r h^2}{3\eta} \quad (3)$$

To obtain a differential equation for h , the equation of continuity is applied, reduction of the height must balance with the radial flux (deBruijne Lammers 1999)

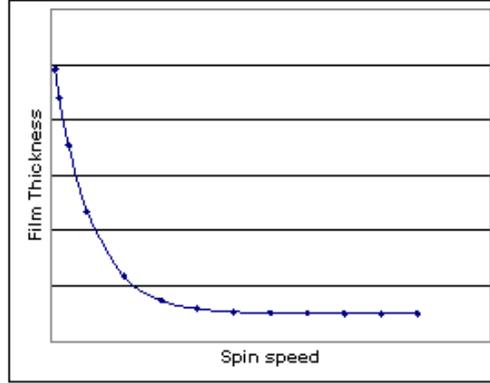


Fig. 2 Relation of the spin speed versus film thickness (Peeters and Remoortere 2008)

$$\frac{\partial h}{\partial t} = -\frac{1}{r} \frac{\partial(rq)}{\partial r} = -K \left(\frac{1}{r} \right) \frac{\partial}{\partial r} (r^2 h^3) \tag{4}$$

where $K = \rho\omega^2 / 3\eta$

Before seeking general solution of Eq. (4), let us consider the special solution which depends only on time t , (Panigrahi *et al.* 2008, Nirajan *et al.* 2009, deBruijne Lammers 1999), thus

$$\frac{\partial h}{\partial t} = -2Kh^3 + 3Krh^2 \frac{\partial h}{\partial r} \tag{5}$$

Since the film is uniform at the beginning, h is independent of r and hence $\partial h / \partial r = 0$ which gives

$$\frac{\partial h}{\partial t} = -2Kh^3 \text{ or } \frac{\partial h}{h^3} = -2K\partial t \tag{6}$$

Eq. (6) is the thinning rate of th coating. Integrating both sides between proper limits, i.e., at $t = 0$, $h = h_0$ and at t , $h = h_t$, we have

$$h = \frac{h_0}{\sqrt{1 + 4Kh_0^2 t}} = \frac{h_0}{\sqrt{1 + \frac{4h_0^2 \rho \omega^2 t}{3\eta}}} \tag{7}$$

where h_0 is the film thickness at time zero (but not physically meaningful because of the first stage ofunstable solution expulsion at early time).

From Eq. (4) and Eq. (5) and relating partial and total derivative as

$$\frac{dh}{dt} = \frac{\partial h}{\partial t} + \frac{\partial h}{\partial r} \frac{dr}{dt} \tag{8}$$

we have $\frac{\partial h}{\partial t} = -2Kh^3$ and $\frac{dr}{dt} = 3Krh^2$

$$\frac{dr}{dt} = \frac{3Kh_0^2 r}{1 + 4Kh_0^2 t} \quad (9)$$

$$\Rightarrow \ln\left(\frac{r}{r_0}\right) = \frac{3}{4} \ln(1 + 4Kh_0^2 t) = \ln(1 + 4Kh_0^2 t)^{3/4} \quad (9)$$

$$\Rightarrow r = r_0 (1 + Kh_0^2 t)^{3/4} \quad (10)$$

Taking the Gaussian initial contour of the form $h_0 = ae^{-\alpha^2 r_0^2}$ or $\frac{h_0}{a} = e^{-\alpha^2 r_0^2}$,

the exponential term is expected to flatter with increase in t (Nirajan *et al.* 2009).

For slowly falling initial contour of the form

$$h_0 = \frac{a}{(1 + \alpha^2 r_0^2)^{3/4}} \quad (11)$$

the flattening due to the exponential is absent (Nirajan *et al.* 2009).

For Gaussian plus uniform initial contour of the form

$$\frac{h_0}{a} = e^{-\alpha^2 r_0^2} \quad (12)$$

the exponential term will lead to flattening with increase in t .

At longer times, solvent evaporation becomes an important contribution to the final film thickness. Meyerhofer was the first to estimate the effect of this on final coating thickness. A quite reasonable approximation is that evaporation is a constant throughout spinning, as long as the rotation rate is held constant. Therefore, he simply added a constant evaporation term to the thinning rate, Eq. (6). So, the governing differential equation became (Hanaor *et al.* 2011, Meyerhofer 1978 and Nirajan *et al.* 2009)

$$\frac{dh}{dt} = -2Kh^3 - e \quad (13)$$

where “ e ” is the evaporation rate [mL/s/cm²] (this is effectively the contribution to the interface velocity that is driven by the evaporation process alone).

Instead of solving this equation explicitly, Meyerhofer assumed that early stages were entirely flow dominated, while later stages would be entirely evaporation dominated. He set the transition point at the condition where the evaporation rate and the viscous flow rate became equal. This can be thought of as the fluid-dynamical “set” point of the coating process and evaporation now depends on rotation rate, ω . Hence

$$e = C\sqrt{\omega} \quad (14)$$

where the proportionality constant, C , must be determined for the specific experimental conditions (Hanaor *et al.* 2011, Meyerhofer 1978 and Hellstrom 2007). This square root dependence arises from the rate-limiting-step being diffusion through a vapour boundary layer above the spinning disk. It should be noted that this results when airflow above the spinning substrate is laminar (Hellstrom

2007).

Let the final film thickness be h_f . Then taking cube-root and rearranging gives

$$h = (2K)^{\frac{1}{3}} \left(-\frac{dh}{dt} \right)^{\frac{1}{3}} - h_f \quad (15)$$

Eq. (15) resembles a straight line equation

$$y = mx + c$$

Therefore, the flow constant, K is determined by the slope and the final film is determined by the intercept.

Meyerhofer developed a spin model using the equation of continuity for a Newtonian fluid but allowed the solvent to evaporate during spinning process. He approximated that the height of the fluid, h could be separated into the height of the solid, S and the height of the solvent, L i.e.,

$$h = S + L$$

The concentration of the solid can be expressed as $C(t)$ so that

$$C(t) = \frac{S}{S + L} \quad (16)$$

From the equation of continuity, one can obtain

$$\frac{dL}{dt} = -C(t) \frac{2\omega^2 h^3}{3\mathcal{G}} \quad (17)$$

where \mathcal{G} is the kinetic viscosity ($= \eta/\rho$). Including the liquid evaporation rate ϕ , the change in liquid height can be expressed as (Nirajan *et al.* 2009)

$$\frac{dL}{dt} = -[1 - C(t)] \frac{2\omega^2 h^3}{3\mathcal{G}} - \phi \quad (18)$$

The viscosities of these solutions have been reported to be the power law function of the concentration which can be written as

$$\mathcal{G} = \mathcal{G}_L + \mathcal{G}_S C^\gamma(t) \quad (19)$$

where \mathcal{G}_L and \mathcal{G}_S are viscosities of solvent and solid respectively and $\gamma = 2.5$. The final film height can be simplified to the form (Nirajan *et al.* 2009 and deBruijne Lammers 1999)

$$\left[\frac{3C^3(t)\mathcal{G}_0\phi}{2\{1 - C_0(t)\}\omega^2} \right]^{\frac{1}{3}} \text{ or } h \propto \omega^{-2/3} \quad (20)$$

In the simplest model of spin coating, which neglects the effect of shear stress, i.e., under slip condition, the final thickness $h(t)$ after time t is related to the initial thickness h_0 by the equation

$$h(t) = \frac{h_0}{(1 + 4Kh_0^2 t)^{1/2}} \quad (21)$$

In the dimensionless sense, we have

$$H \approx \tau^{-1/2}$$

where $H = h(t)/h_0$ is the dimensionless film thickness, $\tau = (2\rho\omega^2 h_0^2 / 3\mu) t$ the dimensionless time.

For a large spinning disk, the air in contact must be exactly co-rotating. However, upper layers of air do not rotate at the same velocity (velocity gradient exists). Since air has finite viscosity, this causes a shearing stress at the interface during the initial stage and is more predominant during “skin formation” at the liquid surface. The film thickness is found to decrease more rapidly compared to the rate of thinning under partial vacuum conditions. Attempts have been made to include the effect of shearing stress in the mathematical modeling of spin coating in order to answer the question. This air flow generates a radially directed shearing force, whose shearing stress magnitude is given by (Nirajan *et al.* 2009, deBruijne Lammers 1999, Panigrahi *et al.* 2008)

$$\tau_{rz} = \frac{1}{2} \omega^{3/2} \nu_{air}^{-1/2} \mu_{air} r. \quad (22)$$

Using suitable boundary condition to account for the shear stress imposed by external air flow and power law behaviour of non-Newtonian fluid, the volumetric flow per unit circumference is given by

$$q = \int_0^h v_r dz = \frac{n}{2n+1} \left(\frac{\rho\omega^2 r}{K} \right)^{1/n} h^{\frac{2n+1}{n}} \quad (23)$$

Using the continuity equation and simplifying yields the solution of the final thickness, $h(t)$ in the form

$$\left(\beta + \frac{1}{H} \right) / (\beta + 1) = \exp \left[\frac{1}{\beta} \left(\frac{1}{H} - \frac{\tau}{\beta} - 1 \right) \right] \quad (24)$$

Similarly in the dimensionless sense we have

$$H \approx \tau^{-1} \quad (25)$$

It is concluded that air shear stress increases the rate of thinning, to the extent $H = \tau^{-1}$ for small H, rather than $H = \tau^{-1/2}$ as expected earlier i.e., without considering the effect of shear stress (Nirajan *et al.* 2009, Schwartz and Roy 2004, Oliveira *et al.* 2012).

3.2 Acceleration

The acceleration of the substrate towards the final spin speed can also affect the coated film properties. Since the resin begins to dry during the first part of the spin cycle, it is important to accurately control acceleration. In some processes, 50% of the solvents in the resin will be lost to

evaporation in the first few seconds of the process (Peeters and Remoortere, 2008).

Acceleration also plays a large role in the coat properties of patterned substrates. In many cases the substrate will retain topographical features from previous processes; it is therefore important to uniformly coat the resin over and through these features (Peeters and Remoortere 2008, Hellstrom 2007).

While the spin process in general provides a radial (outward) force to the resin, it is the acceleration that provides a twisting force to the resin. This twisting aids in the dispersal of the resin around topography that might otherwise shadow portions of the substrate from the fluid (Hanaor *et al.* 2011, Peeters and Remoortere 2008). In operation the spin motor accelerates (or decelerates) in a linear ramp to the final spin speed.

3.3 Fume exhaust

The drying rate of the resin fluid during the spin process is defined by the nature of the fluid itself (volatility of the solvent systems used) as well as by the air surrounding the substrate during the spin process (Middleman and Hochberg 1993). Just as a damp cloth will dry faster on a breezy dry day than during damp weather, the resin will dry depending on the ambient conditions around it (Ilican *et al.* 2008). It is well known that such factors as air temperature and humidity play a large role in determining coated film properties. It is also very important that the airflow and associated turbulence above the substrate itself be minimized, or at least held constant, during the spin process (Middleman and Hochberg 1993, Peeters and Remoortere 2008).

All spin coaters employ a “closed bowl” design. While not actually an airtight environment, the exhaust lid allows only minimal exhaust during the spin process. Combined with the bottom exhaust port located beneath the spin chuck, the exhaust lid becomes part of a system to minimize unwanted random turbulence. There are two distinct advantages to this system: slowed drying of the fluid resin and minimized susceptibility to ambient humidity variations (Middleman and Hochberg 1993, Peeters and Remoortere 2008).

The slower rate of drying offers the advantage of increased film thickness uniformity across the substrates (Middleman and Hochberg 1993, Peeters and Remoortere 2008). The fluid dries out as it moves toward the edge of the substrate during the spin process. This can lead to radial thickness non-uniformities since the fluid viscosity changes with distance from the center of the substrate (Swati *et al.* 2006). By slowing the rate of drying, it is possible for the viscosity to remain more constant across the substrate (Middleman and Hochberg 1993, Peeters and Remoortere 2008).

Drying rate and hence final film thickness is also affected by ambient humidity. Variations of only a few percent relative humidity can result in large changes in film thickness (Peeters and Remoortere 2008). By spinning in a closed bowl the vapours of the solvents in the resin itself are retained in the bowl environment and tend to overshadow the effects of minor humidity variations. At the end of the spin process, when the lid is lifted to remove the substrate, full exhaust is maintained to contain and remove solvent vapours (Peeters and Remoortere 2008).

Another advantage to this “closed bowl” design is the reduced susceptibility to variations in air flow around the spinning substrate. In a typical clean room, for instance, there is a constant downward flow of air at about 100 feet per minute (30 m/min). Various factors affect the local properties of this air flow (Al-Juaid *et al.* 2012). Turbulence and eddy currents are common results of this high degree of air flow. Minor changes in the nature of the environment can create drastic

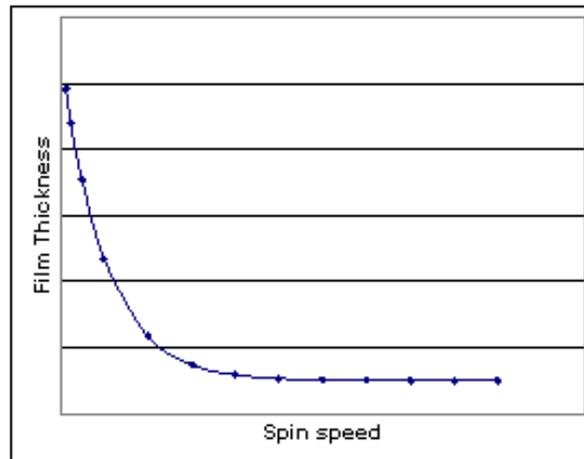


Fig. 3 Some common defects found in spin coating (a) comets; (b) striations; (c) chuck marks (Hanaor *et al.* 2011)

alteration in the downward flow of air. By closing the bowl with a smooth lid surface, variations and turbulence caused by the presence of operators and other equipment are eliminated from the spin process (Mitzi *et al.* 2004).

4. Common defects associated with spin coating technique

4.1 Comets

These usually occur when relatively large solid particles impede the normal flow patterns of the solution on the spinning wafer. Except during "spin up", the flow is normally smooth and radial in nature (having a gradient in radial velocity governed by the applicable force balances and viscosity constraints. See Fig. 3(a) (Hanaor *et al.* 2011). The presence of comets can be reduced or eliminated by working in cleaner environments and by filtering coating solutions as part of the dispense process.

4.2 Striations

Striations are radially oriented lines of thickness variation in the as-coated film. Usually they are quite smoothly varying thickness variations with a spacing or periodicity in the 50-200 micron range, or so. Their orientation corresponds to the direction of major fluid flow. Their occurrence is thought to arise because of evaporation driven surface tension effects (Hanaor *et al.* 2011). The early evaporation of light solvents can cause an enrichment of water and/or other less volatile species in the surface layer. If, the surface tension of this layer is larger than the starting solution (and what still exists at deeper levels), then an instability exists where the higher surface tension actually draws material in at regular intervals and the spaces in-between are more able to evaporate, and surface relief develops as shown in Fig. 3(b). This is essentially due to the Marangoni effect which governs the development of structures in the drainage patterns of wine down the sides of a

wine glass. Ethanol evaporates first leaving an ethanol-depleted wine layer that gathers into rivulets and drains down the glass wall.

The evaporation process makes the top layer have a different composition and therefore a different surface tension. The top surface then can become unstable to “long wavelength” perturbations that grow unstably. The exact conditions that control what is stable and what is unstable are still not well known (Hanaor *et al.* 2011). Our preliminary model is that you would like the evaporation process to be driving the local surface tension to lower values and that this would tend to stabilize the system. This is currently being tested on a number of sol-gel and polymer coating systems (Peeters and Remoortere 2008).

4.3 Chuck marks

These patterns can be created by thermal “communication” between the solution on top of the wafer and the metal vacuum chuck on the back side of the wafer. Thus, the thermal conductivity of the substrate material is very important as is the thermal driving force (mainly evaporative cooling, but could also be due to temperature differences between solution and substrate and chuck). Fig. 3(c) is a single layer sol-gel-derived coating on a glass substrate that illustrates the effect of chuck marks. Silicon wafers, because of their higher thermal conductivity, will usually have smaller thickness differences compared to glass or plastic (Peeters and Remoortere 2008).

4.4 Environmental sensitivity

When making coatings in the ambient environment, it is possible for the surroundings to have an influence on the coating quality. One critical variable is the humidity of the surrounding air. For many solutions, water can play an important role in the chemistry of the solution itself, so when varying amounts of water are present in the surroundings then varying coating quality can result. This can manifest itself as coating roughness, microcracking of the coating upon further drying, exaggerated striation formation in the coating, etc. Obviously, close control of the environment around the spin coater is crucial to minimize environmental sensitivity effects.

4.5 Wafer edge effects

The edges of the substrate will always be areas of concern. If better uniformity can be maintained out to the edges then more area can be used for device fabrication. The edges are problems for several reasons. First, surface tension effects make it difficult for solution that is flowing radially outward to detach from the wafer. Thus a small “bead” of liquid can stay attached around the entire perimeter and result in thicker coatings in this rim zone. In addition, if substrates are not exactly round and especially if they are square or rectangular, then the air flow over the protruding parts (corners) will be perturbed. Although the flow may still be laminar, it will have different flow history and will usually result in non-uniformity in coating thickness in these corner areas.

5. Discussion

There is a wide range of thin film deposition techniques in existence, such as wet chemical methods (Verges *et al.* 1990, Vayssieres *et al.* 2001), physical vapor deposition (Pan *et al.* 2001, Huang *et al.* 2001), metal–organic chemical vapor deposition (MOCVD) (Yuan and Zhang 2004), molecular beam epitaxy (MBE) (Heo *et al.* 2002), pulsed laser deposition (Hong *et al.* 2009), sputtering (Chiou *et al.* 2003), flux methods (Xu *et al.* 2002), eletrospinning (Lin *et al.* 2007, Sui *et al.* 2005), spin coating and even top-down approaches by etching (Wu *et al.* 2004). Among those techniques, physical vapor deposition and flux methods usually require high temperature, and easily incorporate catalysts or impurities into the film nanostructures. Therefore, they are less likely to be able to integrate with flexible organic substrates for future foldable and portable electronics and some other applications. MOCVD and MBE can give high quality nanowire arrays of semiconductor compounds such as ZnO, but are usually limited by the poor sample uniformity, low product yield, and choices of substrate. Also, the experimental cost is usually very high, so they have been less widely adopted. Pulsed laser deposition, sputtering and top down approaches have less controllability and repeatability compared with other techniques. Electrospinning gives polycrystalline fibers.

Comparatively, spin coating technique is an attractive technique for thin film deposition for several reasons: it is low cost, less hazardous, and thus capable of easy scaling up (Zhang *et al.* 2006), growth occurs at a relatively low temperature, compatible with flexible organic substrates; there is no need for the use of metal catalysts, and thus it can be integrated with well-developed silicon technologies (Xu and wang 2011). In addition, there are a variety of parameters (spin speed, time of spin, acceleration, fume exhaust, etc.) that can be tuned to effectively control the morphologies and properties of the final products (Chang and Lu 2008). Spin coating technique have been demonstrated as a very powerful and versatile technique for growing nanostructures of several group II-VI compound semiconductors. Controllability and repeatability of the coating process is a prominent characteristic of remarkable advantage in spin coating technique, which also enables a firm control on the morphologies and properties of the produced films.

Spin coating has many advantages in coating operations with its major advantage being the absence of coupled process variables. Film thickness is easily changed by changing spin speed, or switching to a different viscosity photoresist. But among the alternative coating techniques, many have multiple coupled parameters, making coating control more complex. Another advantage of spin coating is the ability of the film to get progressively more uniform as it thins, and if the film ever becomes completely uniform during the coating process, it will remain so for the duration of the process. It is low cost and fast operating system. The maturity of spin coating implies that many of the issues involved in spin coating have been studied and a lot of information exists on the subject.

Inspite of outstanding advantages, spin coating have few disadvantages but they are becoming more important as substrate size increases and photoresist costs rise. Large substrates can not be spun at a sufficiently high rate in order to allow the film to thin. Its major disadvantage is the lack of material efficiency. Typical spin coating processes utilize only 2-5% of the material dispensed onto the substrate, while the remaining 95-98% is flung off in to the coating bowl and disposed. Not only are the prices of the photoresist increasing substantially, but disposal costs increasing as well. If economically feasible manufacturing costs are to be maintained, a method for improving this material utilization is of primary importance, especially in the flat panel display area (Panigrahi *et al.* 2008, Washo 1977). However, on the strictest note, the spin coating technique can be viewed as a simple, less expensive and less hazardous technique that can yield an excellent

result when properly handled.

6. Conclusions

The theory of the spin coating technique has been presented and spin coating models are used to describe the spin coating process for material systems that behave in a Newtonian and non-Newtonian manner. The basic principles and parameters controlling the process such as spin speed, time of spin, acceleration, fume exhaust are clearly highlighted. This will probably achieve a basic aim of educating current researchers in the area of thin film production, to enhance the best use of this technique.

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